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Empirical Analysis on the Effect of Gross Vehicle Weight and Vehicle Size on Speed in Car Following Situation

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Abstract: This study attempts to explore empirically how gross vehicle weight (GVW) of following vehicle and size of leading vehicle will affect the driver behavior in controlling their speed under different compositions of leader-follower pairs in a car-following situation. A large sample of traffic and vehicular data for various vehicle types were obtained continuously using a weigh-in-motion (WIM) based transport data collection system installed at Federal Route 54 in Malaysia. Then, statistical analysis was applied to explore the driver behavior in controlling the speed in a car-following situation from two different perspective: driver's visual input and vehicle dynamics capability. The main findings of this study are when we incorporate the vehicle dynamic's capability in a car-following situation, the GVW of following vehicle and the size of leading vehicle were significant sources of variation in following vehicle speed and relative speed, and their interaction influence the driver behavior in controlling the speed.

Key Words: *Weigh-in-motion (WIM), Gross Vehicle Weight (GVW), car-following, speed analysis*

1. INTRODUCTION

Vehicle as one of the important element in a traffic stream is completely a dynamic system. Equation of motions of vehicle dynamics can be found in many references related to fundamental of vehicle dynamics such as Wong J. Y. (1993) and R. N. Jazar (2008), which are derived analytically from Newton's fundamental law. From macroscopic approaches, traffic stream models, either in two-variable or in three-variable models, is the relationship among speed, flow (vehicles/hour), and concentration (whether density or occupancy) (Gartner N. H. *et. al.*, 1992). Values of these variables of interest are obtained as a function of many implicit factors including vehicle dynamics. Thus, it can be said that implicitly vehicle dynamics is considered in the model development.

On the other hand, microscopic traffic flow models focus on a single vehicle-driver unit. To date, one of the popular topics among the family of microscopic traffic models is a car-following model (Brackstone and McDonald, 1999). In deriving the models, the previous researches have made many assumptions to greatly simplified by merely describing the driving strategies of drivers in response to the leading vehicles.

As mentioned in Wang L. J. *et. al*., (2008), car following strategies can be divided into two classes: the driver is assumed to maintain a safe distance to the leading vehicle by controlling his own speed (Chandler R. E. *et al*., 1958), and the desired speed of the following vehicle depends on the gap distance with respect to the leading vehicle (Bando M. *et al*., 1995). In order to reach good agreement with the field data, many improvements have been done to both classes of the model among them are introducing sensitivity function (Chung S. B. *et al*, 2005; Chang K and Chon K., 2005), considering the headway of the immediately preceding one (Sawada, S. 2002), considering the effect of environments on driver behavior in a car-following situation (Ni, R., *et al*., 2010), considering the effect of curve or intersection (Suzuki H., *et al*., 2005) and considering the effect of driving style due to the different compositions of a leader-follower pair (Ossen S. and Hoogendoorn S. P., 2011).

However, the previous researches only address the modeling of car-following situation arising from driver behavior perspective. The characteristics of the vehicle such as performance, braking and acceleration capability is assumed to be same for all type vehicles and for different compositions of a follower-leader pair in the model development. The main reason is in the past it is difficult to obtain the weight, speed, acceleration and classification data simultaneous and continuously over the period of time without disrupting the natural way of traffic flow.

As mentioned in Wong J. Y. (1993), the behavior of a ground vehicle represents the results of the interactions among the driver, the vehicle, and the environment. Most of the time the vehicle dynamics influence drivers behavior in controlling their vehicles. Thus, the model can be improved to be more realistic if the vehicle dynamics is incorporated.

In this study, among other factors that can affect the vehicle dynamics, this study attempts to explore and to provide a valid empirical evidence that following vehicle (FV) GVW and leading vehicle (LV) size will affect the driver behavior in controlling their speed under different compositions of leader-follower pairs (different weight of followers follows different size of leaders) in a car-following situation.

The vehicle weight is one of the essential parameters in vehicle design study that can affect vehicle driving, braking and handling performance characteristics (Bixel A. R. *et al*, 1998). The effect of weight on commercial vehicle performance is more considerable compared to a non-commercial vehicle.

In discussing on the development of the relationships or empirical models, the link with measurement capability of a transport data collection system is very important in order to have a practical and realistic model.

The emerging technology in a measurement field recently is undoubtedly changing the way some traffic measurements are obtained and will likely provide the opportunity for acquiring more and better data to further advance understanding of the fundamental issues. One of the most difficult tasks related to measurement capability is to obtain weight data of moving vehicle. The only prominent technology used to obtain weight data is weigh-in-motion (WIM) technology. For the purpose of this study, a comprehensive, accurate and reliable traffic and vehicular data collection system using quartz weigh-in-motion sensor has been developed for measuring the speed, class, GVW, time headway and other traffic and vehicular data simultaneously and continuously 24 hours and 7 days. Further elaboration of the developed system is presented in (Saifizul A. A. *et al.*, In press).

2. THE DATA COLLECTION SYSTEM

The quartz WIM sensor is used to measure related traffic and vehicular data and schematic diagram of the developed system is shown in Figure 1 and 2.

Figure 1. The data collection system layout

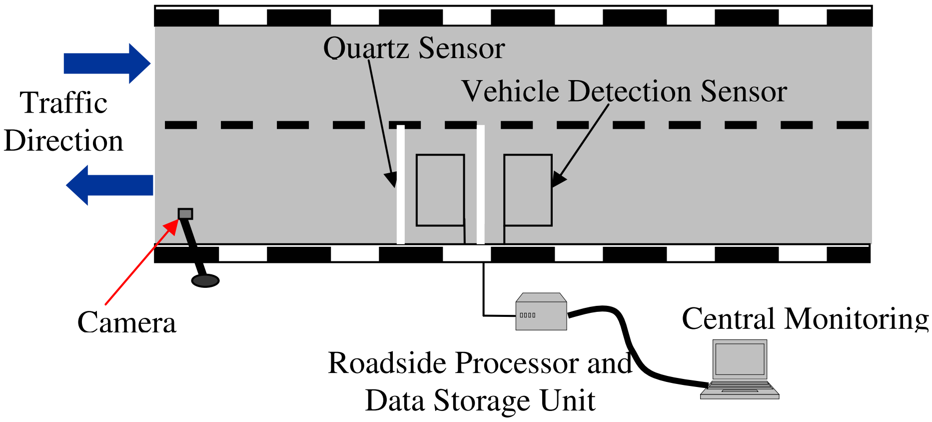

Fig. 2. Schematic diagram of WIM system layout

The data-collection system was installed on Federal Route 54 which located 35 km from the city center and the traffic direction move from city to a rural area. Road type is rural single carriageway with standard width and layout and road geometry is a straight and flat road. The traffic composed of high proportion of a commercial and non-commercial vehicle.

When a force is applied to the sensor surface, the quartz disks yield an electric charge that is proportional to the applied force through a piezoelectric effect. Then, the electric charge is converted by a charge amplifier into a proportional voltage, which then must be further processed as required. The sensor must be integrated into the road surface and is, thus, only viable for permanent installation applications. As a vehicle starts to drive over the sensor, the software begins gathering data. Data is gathered until the vehicle's entire axle has passed completely over the sensor. When this is complete, the software analyzes the data that was captured to determine the desired parameters, such as speed, wheelbase, GVW, number of axles, and other parameters.

3. RESULTS

The following behavior of a driver can be affected by various internal factors and its surrounding such as driver's condition and vehicle dynamic characteristics, and changes in roadside infrastructure, traffic condition, road geometry condition and sight distance due to weather and day or night condition. Because the objective of this study is to provide a valid empirical evidence that following vehicle (FV) GVW and leading vehicle (LV) size affect the following behavior, real data should be carefully selected to minimize the errors caused by changes in the surroundings. In addition, the collected real data is a mixture of restrained and unrestrained vehicles. The analysis should only consider the case of restrained vehicles where the follower and its leader have influence on each other.

A total of more than 500,000 data was collected in four months from the system. For the purpose of this study, in order to remove the influence of the surroundings and concentrate on the driver behavior in a car-following situation, data were filtered based on following conditions:

- Dry weather condition
- Daytime from 7am (after sunrise) and before 7 pm (before sunset)
- No change in the infrastructure and surrounding at the site
- Time headway less than 4 s (assuming the follower and its leader have influence on each other if the time headway is less than 4s)

After the filtered, total number of samples reduced to 61,381. The speed data (FV speed and relative speed) are then grouped according to FV GVW and LV wheelbase (19 FV GVW range and 3 LV wheelbase range, as wheelbase directly related to vehicle size). There are total 57 groups of data. Normal test has been performed for each group of data and all data can be considered having normal distribution with slightly different in Skewness and Kurtosis. Number of sample for each group is given in Table 1.

Table 1 Number of sample of each group

GVW Range (t)	<2.5	2.5-5	5-7.5	7.5-10	10-12.5	12.5-15	15-17.5	17.5-20	20-22.5
Case1	10986	3913	3807	1512	1307	1461	1363	786	429
Case2	10921	2402	965	400	336	372	357	229	168
Case3	8998	1993	508	249	196	245	232	164	133

GVW Range (t)	22.5-25	25-27.5	27.5-30	30-32.5	32.5-35	35-37.5	37.5-40	40-42.5	42.5-45	>45
Case1	382	372	276	309	430	519	435	365	227	253
Case2	151	156	115	120	210	201	216	144	113	121
Case3	147	144	117	154	267	311	262	203	108	121

To simplify the results generation and analysis, the analysis is divided into three cases according to LV wheelbase range as mentioned earlier and is shown in Table 2.

Table 2. Three cases according to LV wheelbase range

	LV Wheelbase		
	<3m (Small size)	3-5m (Medium size)	>5m (Large size)
FV Speed (All FV GVW Range)	Case 1	Case 2	Case 3

3.1 Analysis on Speed of Following Vehicle

The line plots of mean and standard deviation of following vehicle speed as a function of GVW for all cases (following various sizes of leading vehicle) are shown in Figure 3 and 4.

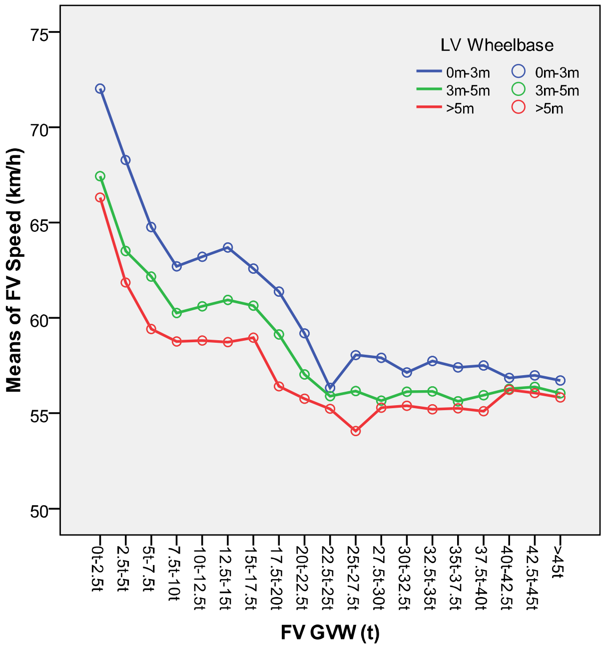

Figure 3: Means plot of FV speed for all cases

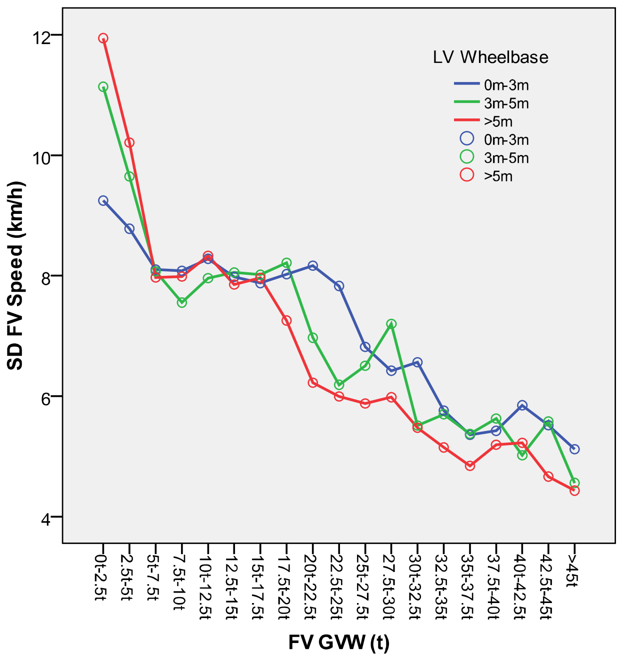

Figure 4: Standard Deviation plot of FV speed for all cases

The relationship is based on the assumption that a linear relationship exists between the mean of FV speed and the logarithm of the mean FV GVW, and between the standard deviation of FV speed and the mean of FV GVW as express in Equation (1).

$$\begin{aligned} \mu_{FV} &= C_1 \log w + C_2 \\ \sigma_{FV} &= C_3 w + C_4 \end{aligned} \qquad (1)$$

where μ_{FV} and σ_{FV} are means and standard deviation of FV speed and w is FV GVW. Coefficients of the regression lines, C_i where $i=1,2,3,4$ in Equation (1) and coefficients of determination, R^2 for all cases can be described as in Table 3:

Table 3 Regression coefficients with p-value and coefficients of determination of the FV mean and standard deviation speed

	C_1	C_2	C_3	C_4	R^2 (Means)	R^2 (SD)	N
Case 1	-10.355	73.505	-.089	9.223	.939	.907	19
(p-value)	<0.001	<0.001	<0.001	<0.001			
Case 2	-7.791	68.274	-.109	9.600	.922	.841	19
(p-value)	<0.001	<0.001	<0.001	<0.001			
Case 3	-6.792	65.797	-.130	9.859	.881	.847	19
(p-value)	<0.001	<0.001	<0.001	<0.001			

Regression coefficients in Table 3 indicate that an exponential relationship between mean of FV speed and FV GVW. In this case, mean of FV speed decreases very rapidly as mean of FV GVW first increases, but then decreases much less rapidly as mean of GVW increases further. The value of coefficients also indicates that the estimation of intercept and slope may change under different cases (Case 1 to Case 3), but the forms of the relations should remain valid.

In case of standard deviation, a negative straight-line or linear relationship between standard deviation of FV speed and FV GVW. However, there were some differences in the gradients of regression lines for all three cases. In the case where light vehicles follow small size vehicles, the speed variation is substantially lower than when they follow large size vehicles. This situation is different for a heavy vehicle. The speed variation is small when heavy vehicles follow large size vehicles compared to small size vehicles.

Table 3 also indicate that the estimate of the slope and intercept for Equation (1) is significantly different from zero and the model adequately described the data (for each case, $p < 0.001$).

3.2 Analysis on Relative Speed

In the previous subsection, the effect of LV speed on a car-following situation was not taken into consideration. By assuming that the leading vehicle was constantly speeding at the recorded speed after passing through the sensor until the following vehicle touches the sensor, the effect of FV GVW and LV size on relative speed in car following situation can be performed. The relative speed in this study is defined as follows:

$$\Delta V = V_{LV} - V_{FV} \qquad (2)$$

where V_{LV} and V_{FV} are speed of leading and following vehicle, respectively.

The line plots of mean and standard deviation of relative speed as a function of GVW for each case are shown in Figure 5 and 6.

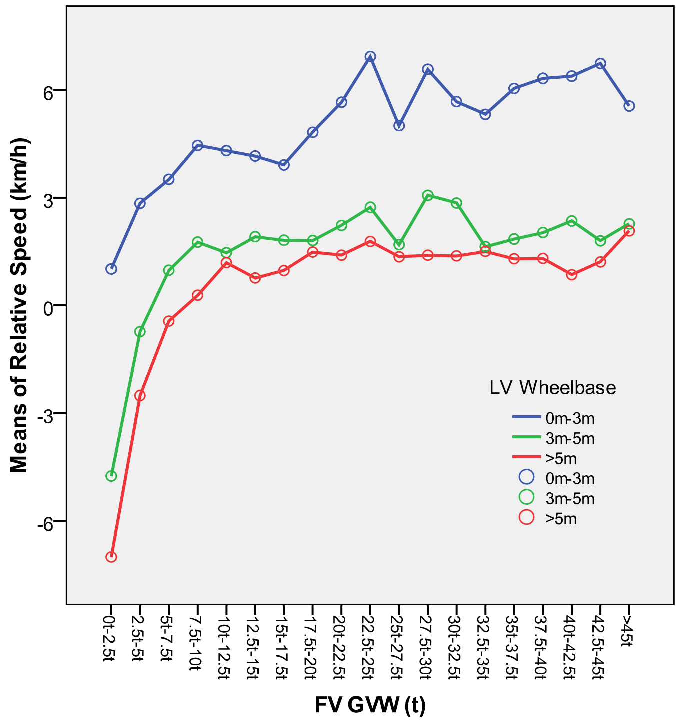

Figure 5. Means plot of Relative Speed for all cases

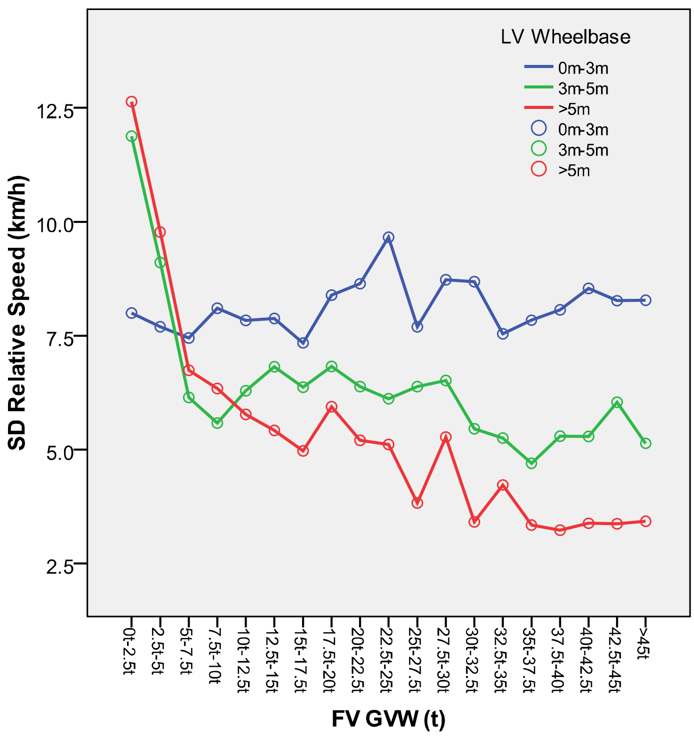

Figure 6. Standard deviation plot of Relative Speed for all cases

For the case of relative speed, the relationship is based on the assumption that a positive curvilinear relationship exists between both the mean of FV GVW and the relative speed, and the standard deviation of relative speed and the mean of FV GVW as express in Equation (3).

$$\begin{aligned} \mu_{\Delta V} &= D_1 \log w + D_2 \\ \sigma_{\Delta V} &= D_3 \log w + D_4 \end{aligned} \qquad (3)$$

where $\mu_{\Delta V}$ and $\sigma_{\Delta V}$ are means and standard deviation of relative speed and w is FV GVW. Coefficients of the regression lines, D_i where $i=1,2,3,4$ in Equation (3) and coefficients of determination R^2 for all cases can be described as in Table 4:

Table 4 Regression coefficients with p-value and coefficients of determination of mean and standard deviation of relative speed

	D_1	D_2	D_3	D_4	R^2 (Means)	R^2 (SD)	N
Case 1	3.355	.816	.426	7.604	.843	.099	19
(p-value)	<0.001	=0.094	=0.190	<0.001			
Case 2	3.546	-2.921	-3.391	10.640	.724	.733	19
(p-value)	<0.001	<0.001	<0.001	<0.001			
Case 3	4.484	-5.066	-5.621	12.367	.784	.929	19
(p-value)	<0.001	<0.001	<0.001	<0.001			

Regression coefficients in Table 4 indicate that the means of relative speed is increasing rapidly as the means of FV GVW increases, but this increase tapers off beyond certain values of mean FV GVW (i.e. in this case 10 tonne).

For the case of standard deviation, the coefficients of determination and the p-value of the slope coefficient for Case 1 indicate that the slope coefficient is not significantly different from zero and the relative speed is not affected by FV GVW. However, the situation is different for Case 2 and Case 3, where the variance of relative speed decreases very rapidly as mean of FV GVW first increases, but then decreases much less rapidly as mean of GVW increases further.

Table 4 also indicate that the estimate of the slope and intercept for Equation (3) is significantly different from zero and the model adequately described the data (for each case, $p < 0.001$ except for Case 1 standard deviation).

4. DISCUSSION

The main findings of this study are when we incorporate the vehicle dynamic's capability in a car-following situation, the GVW of following vehicle and the size of leading vehicle were significant sources of variation in FV speed and relative speed, and their interaction influence the driver behavior in controlling the speed. More specific, indications are found that the driver's ability to achieve its desired speed is not only impeded by leading vehicle size and leading vehicle speed but also constrained by its vehicle weight.

In vehicle design study (as given in the aforementioned reference), the vehicle weight directly affects a variety of vehicle characteristics, including traction, braking and handling characteristics. Thus, most countries imposed additional requirements or training to heavy vehicle drivers. The following subsections provide more details discussion of the results of statistical tests.

4.1 Effects on Speed of Following Vehicle

The results indicate that average speed of FV is decreasing with an increase in its GVW would most probably due to the driver's understanding the heavy vehicle limitations and/or may also due to the heavier vehicle has fewer dynamic performance capabilities. In case where following vehicles follow various sizes of leading vehicles, the average speed of FV also decreases with an increase in LV size. This may due to the large size vehicle can obstruct the visibility of the driver beyond LV and/or FV being impeded by LV speed because vehicle size is inversely proportional to the speed. The same phenomena can be observed for heavy vehicle.

Results from linear regression also show that the variance of FV speed decreases with an increase in FV GVW, which may also due to vehicle dynamic's limitations. The speed variance of light FV is larger when follow large LV in comparison to follow small LV. However, the results show a reverse effect when heavy vehicles follows various sizes of LV as shown in Figure 4. The speed of heavy vehicles has less variance when follow large LV compared to small LV. One possible reason of the observed is that light or small vehicles have better performance capability, which may allow the driver to accelerate or decelerate faster. The following subsection further discusses the results when LV speed is taken into consideration.

4.2 Effects on Relative Speed

Regression plots of an average relative speed show that for Case 1 (following small size vehicle), the relative speed increase as mean of FV GVW increases. The results obviously show that light vehicles do not have difficulty achieving its desired speed or maintain closely with LV speed.

However, for heavier vehicles, the drivers are constrained by its vehicle dynamic's capability and the positive values of the average mean relative speed show that most of the time they are unimpeded by the speed of their small size leading vehicles.

Furthermore, we can also observe that when light vehicles follow medium or large size vehicles, their average speed is slightly higher than the leader may because, with better dynamic's capability, they were trying to follow the leader speed (especially when the gap distance allows them to accelerate) or in a process of attempting to overtake the leading vehicle.

But why, then did heavy vehicles when follow small size vehicles have the same variation of relative speed as given in Figure 6? We postulate that result can be explained as light and small vehicles the drivers do not being constrained by its vehicle performance capability cause them to drive as they like. There are a situation where the follower keeps away from the leader (positive relative speed) or the follower accelerates to get close to the leader (negative relative speed). But in the case of heavy vehicles following small size vehicle, the relative speed variation mainly caused by the loading that they carried. If the loading is within the vehicle design specification, the heavy vehicle drivers are able to achieve their leader speed or impeded by them as long as the leader speed is within their maximum vehicle capability. However, most of the cases, as shown in Saifizul A. A. et. al. (In Press), in

Malaysia, each vehicle class (according to the number of axle and wheelbase) can have large variation in GVW. For instance, there appear a difference in dynamic capability between 3 axle trucks and 5 axle trucks when both carry 50 tonne loads. Because of constraints in it dynamic's capability, obviously the driver of 3 axle trucks cannot drive at the same speed as 5 axle trucks. This cause a variation in relative speed when they follow a passenger car even though in both situations they are not always impeded by leader speed. The sketch of the proposed relationship among FV speed and GVW, and LV size, and among relative speed, FV GVW and LV size are given in Figure 7 and 8.

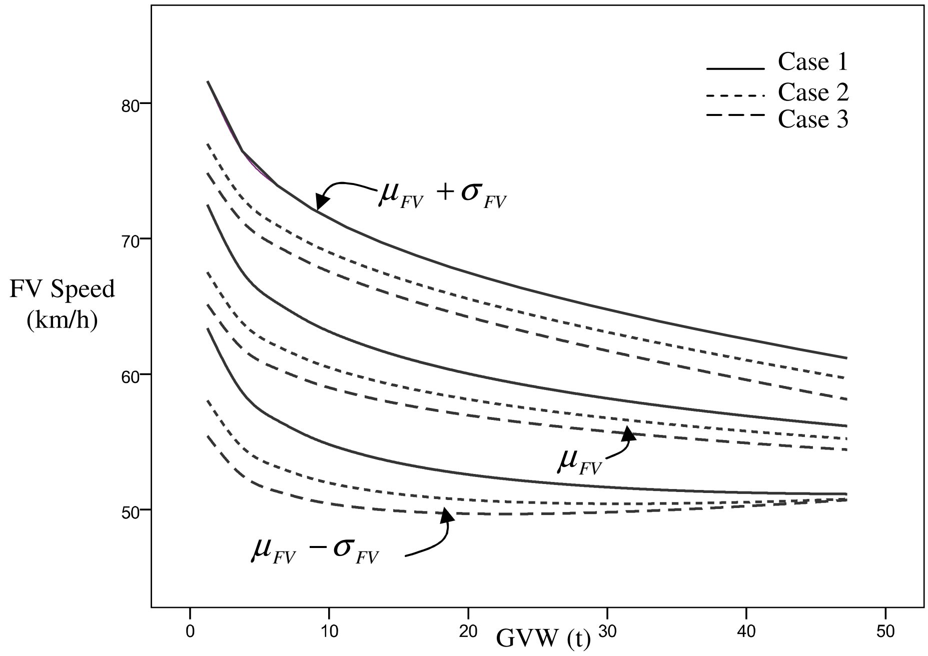

Figure 7 The proposed relationship among FV speed, FV GVW and LV size

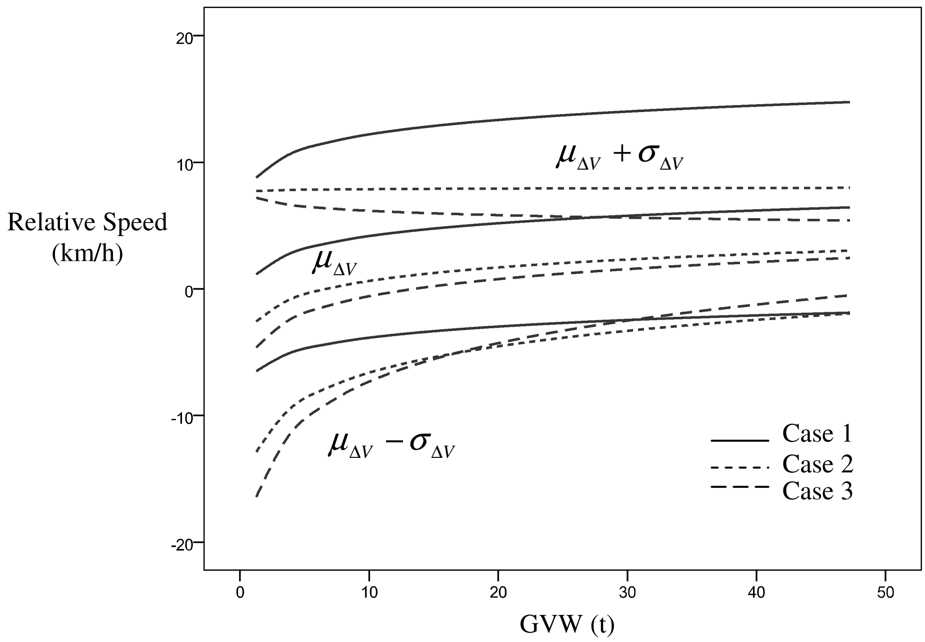

Figure 8. The proposed relationship among relative speed, FV GVW and LV size

5. CONCLUSION

Empirical analysis of car-following situations with different compositions of follower-leader pairs in terms of weight and size were done based on real data collected from the developed continuous, reliable, accurate and comprehensive traffic and vehicular data collection system.

Analysis explored the driver behavior in controlling the speed under car-following from two different perspective: driver's visual input and vehicle dynamics capability as shown in Figure 9.

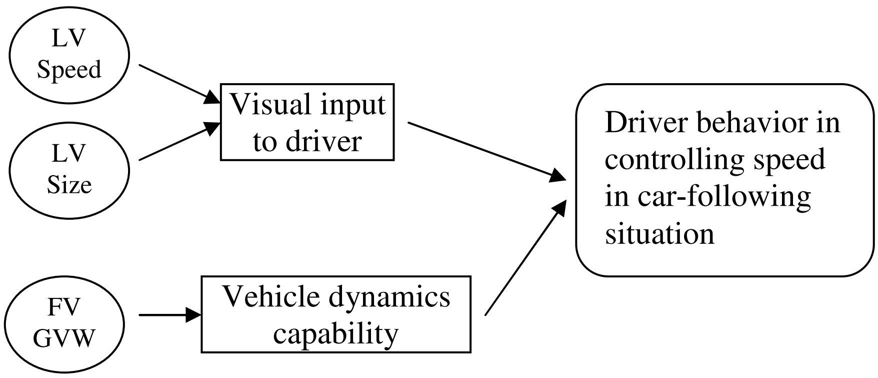

Figure 9 Significant source of variation in speed in car-following situation

The results of this study may be summarized as follows:

1. The study suggests that the FV GVW, LV size and LV speed were significant sources of variation in FV speed.
2. Drivers of a heavy vehicle in average are constrained by their vehicle dynamic's limitations. In the case where the leader has better performance capability, the results, in average, show that the heavy vehicle followers are unable to maintain closely with the speed of small size leader vehicles.
3. Whereas, in the case where the follower-leader pair has almost same performance capability or the follower has better performance capability, the follower in average is impeded by its leader speed and/or size.
4. Light and heavy vehicles maintain different safe desired speed with LV according to LV size. This can be caused by the large vehicle moved at a low speed in comparison to small size leading vehicle or FV drivers cannot anticipate future traffic conditions due to drivers visual regarding the forward scene may be obstructed by large size vehicle.
5. The observation provides a preliminary step for considering vehicle weight as an additional variable of interest in a car-following study.

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